CP violation in B decays:
Search for Physics beyond the Standard Model

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Outline

Will cover three sets of measurements that have the potential to reveal effects of physics beyond the SM:

- **“sin2β” measurements in b->s penguin decays** 
- **Direct CP violation in B decays**
- **Polarization effects: Revisit b->sγ_L**

The CKM Test (*covered in Kazuo Abe's Talk*)

A successful test so far: CP violation in kaons (ε_K, ε'_K) ,CP conserving observables (Vub, Vcb, Δm_d, Δm_s) & CPV in B decays (sin2β), α & γ all fit within the CKM picture with a single CP breaking phase.

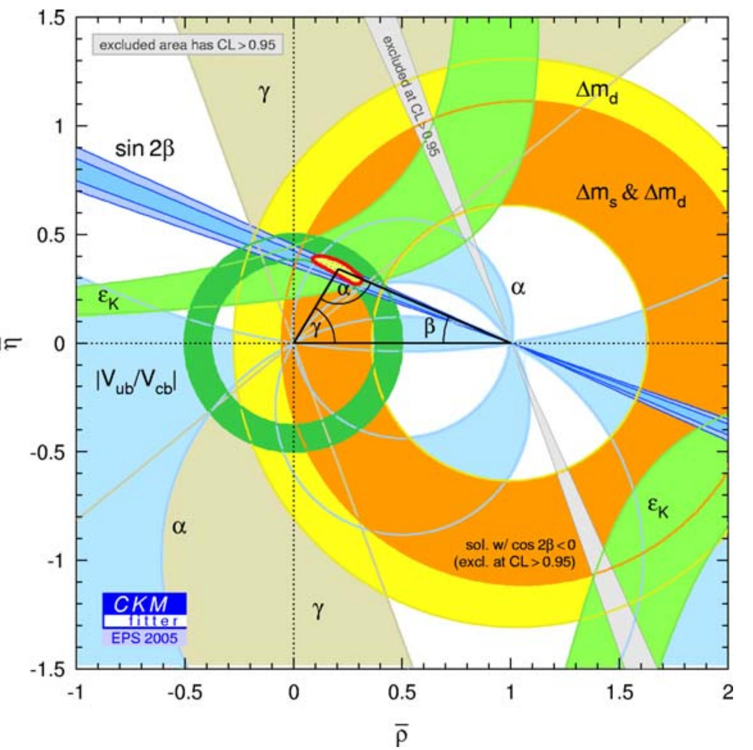
So, what does this mean for "New Physics" in the flavor sector?

From L. Silvestrini's talk at Lepton-Photon 2005 (Direct quote/copy)

- New sources of CPV in $s \to d$ and/or $b \to d$ transitions are
  - strongly constrained by the UT fit
  - "unnecessary", given the great success and consistency of the fit
- New sources of CPV in $b \to s$ transitions are
  - much less (un-) constrained by the UT fit
  - natural in many flavour models, given the strong breaking of family SU(3)

    Pomarol, Tommasini; Barbieri, Dvali, Hall; Barbieri, Hall; Barbieri, Hall, Romanino; Berezhiani, Rossi; Masiero et al; …
  - hinted at by ν's in SUSY-GUTs

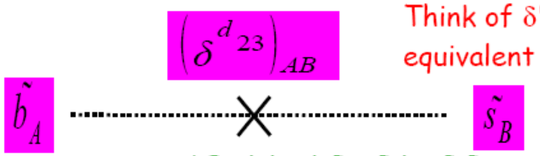
    Baek et al.; Moroi; Akama et al.; Chang, Masiero, Murayama; Hisano, Shimizu; Goto et al.; …



Are these effects measurable via CP asymmetries in B decays?

Again borrowing from L. Silvestrini's talk at Lepton-Photon 2005:

- We consider a MSSM with generic soft SUSY-breaking terms, but
  - dominant gluino contributions only
  - mass insertion approximation



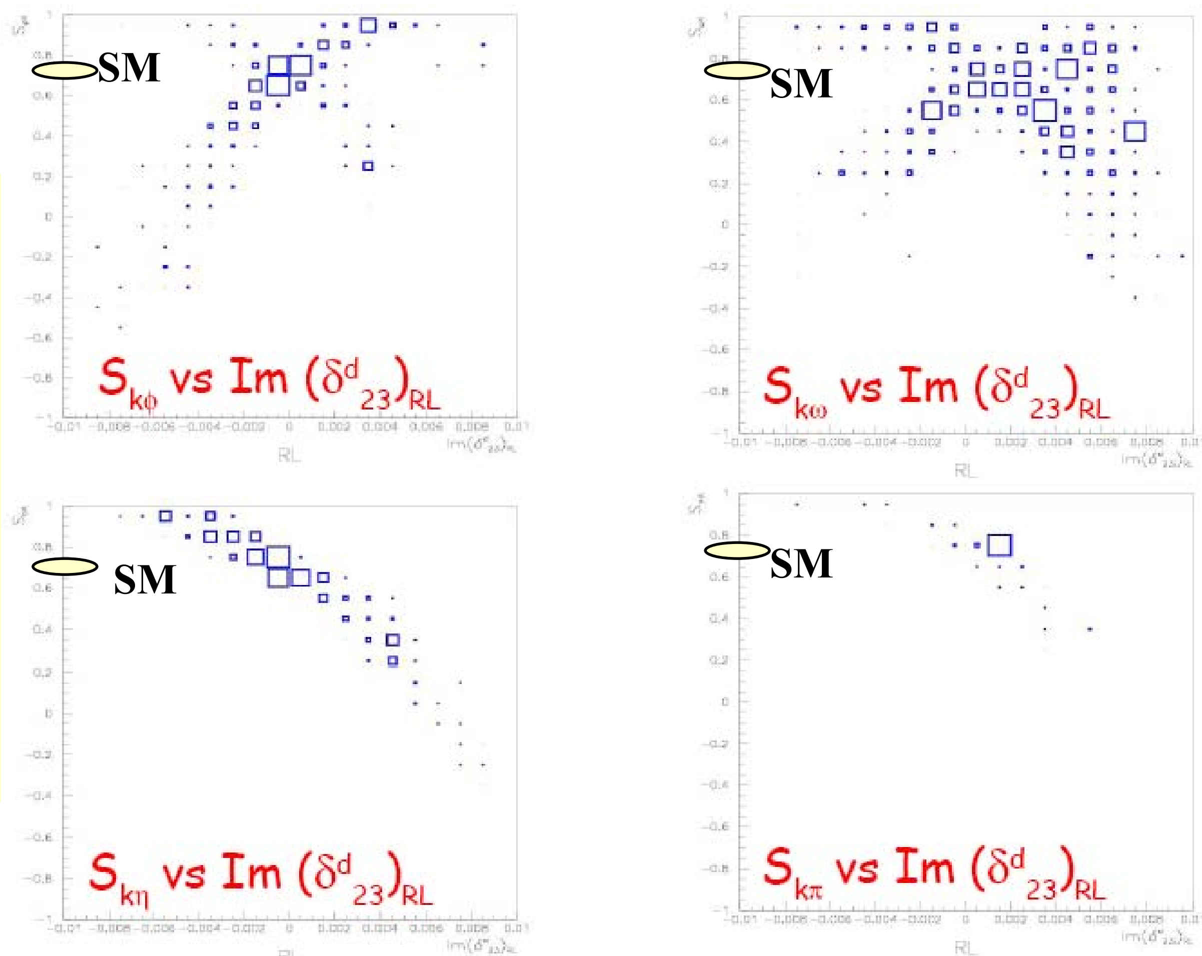
Think of δ's as SUSY equivalent of CKM mixing

four insertions AB=LL, LR, RL, RR

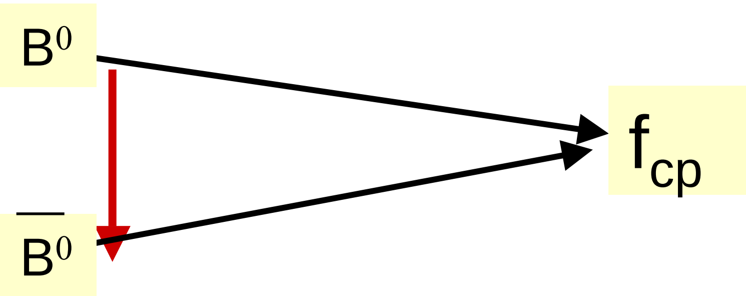
- Can alter both the S and C terms of the time dependent $A_{cp}(T)$
- Change polarization properties of the final states.

➢ **Significant deviations from the SM expectation for CP asymmetries is possible and detectable with current experiments**

➢ **Failure to see any, will lead to constraints on new mixing angles and new phases**

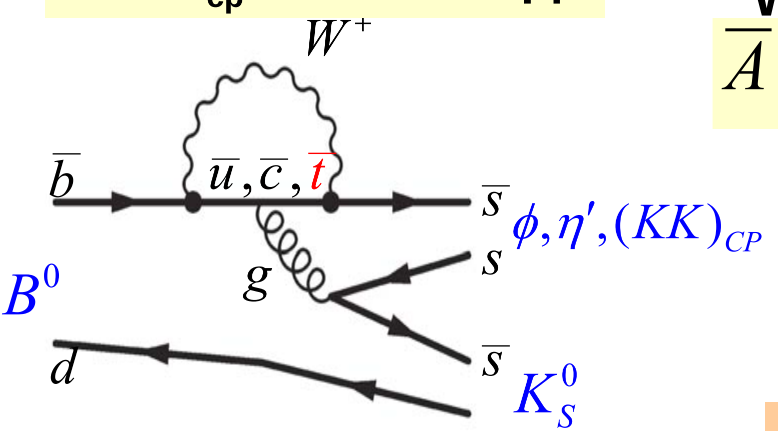


The "sin2β" Test: Mixing induced CP violation in penguin modes b->sq$\bar{q}$



$$A_{cp}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{cp}) - \Gamma(B^0(t) \to f_{cp})}{\Gamma(\bar{B}^0(t) \to f_{cp}) + \Gamma(B^0(t) \to f_{cp})} = S\sin\Delta mt - C\cos\Delta mt$$

For f_{cp} =from b->sq$\bar{q}$



Within the SM:

$$\bar{A} = V_{cb}V_{cs}^*[P_c - P_t + T_c] + V_{ub}V_{us}^*[P_u - P_t + T_u]$$

Dominant amplitude (~λ^2)– same phase as b->c$\bar{c}$s

suppressed amplitude (~λ^4)

Expect within SM

$S_f \sim -\eta_{cp}\sin2\beta$

With new physics and new phases, S_f could depart from $-\eta_{cp}\sin2\beta$

The Task: Measure $\Delta S_f = -\eta_{cp}S_f - \sin2\beta$ & search for deviation from zero

A Key Question: How well do we know ΔS_f within the SM?

SM expectation

Within the SM:

$$\overline{A} = V_{cb} V_{cs}^{*} [P_c - P_t + T_c] + V_{ub} V_{us}^{*} [P_u - P_t + T_u]$$

Dominant amplitude ($\sim\lambda^2$)– same phase as b->c$\bar{c}$s

suppressed amplitude ($\sim\lambda^4$)

ΔS_f depends on the size and the relative strong phase of this "suppressed " term

QCDF calculations(Beneke, hep-ph/0505075 Cheng, Chua & Soni, hep-ph/0506268).

Decay mode	$-\eta_f S_f^{SM} - S_{X_{cc}}^{SM}$ QCDF based Allowed range	$\lvert -\eta_f S_f^{SM} - S_{X_{cc}}^{SM} \rvert$ SU(3) based Upper bound
X_{cc}	–	–
ϕK^0	$+0.01 < \Delta S_f < 0.05$	$\lvert\Delta S_f\rvert < 0.5$ (0.19*)
$\eta' K^0$	$+0.0 < \Delta S_f < 0.03$	$\lvert\Delta S_f\rvert < 0.21$ (0.14*)
$\pi^0 K^0$	$+0.02 < \Delta S_f < 0.15$	$\lvert\Delta S_f\rvert < 0.18$
ωK^0	$+0.01 < \Delta S_f < 0.21$	$\lvert\Delta S_f\rvert < 0.58$
$f^0 K^0$	–	–
$K^+K^-K^0$	$\Delta S_f \approx +0.10^{+0.06}_{-0.09}$	$\lvert\Delta S_f\rvert < 0.71$ (0.19*)
$K_S^0 K_S^0 K_S^0$	$\Delta S_f \approx +0.02^{+0.00}_{-0.04}$	$\lvert\Delta S_f\rvert <$ (0.30*)
$\rho^0 K^0$	$-0.29 < \Delta S_f < 0.02$	$\lvert\Delta S_f\rvert < 0.49$
ηK^0	$-1.67 < \Delta S_f < 0.27$	–

SU(2) and SU(3) can also be put to work to connect various CP conserving and CP violating observables-- generally much less restrictive- but can improve with data.

The $b \to s q\bar{q}$ penguin decays used in the "$\sin 2\beta$" test

Need decays into CP eigenstates f_{cp} :

$b \to s s\bar{s}$:

$B \to \phi K_s$ (η_{cp}=-1)
$B \to \phi K_L$ (η_{cp}=+1)
Br=8.3+/- 1.1 x10^{-6}

$B \to K^+K^-K_s$ (η_{cp}=+1 dominates)
$B \to K^+K^-K_L$ (η_{cp}=-1 dominates)
Br=6.2+/- 0.9 x10^{-6}

$B \to K_sK_sK_s$ (η_{cp}=+1)

$B \to \eta' K_s$ (η_{cp}=-1)
$B \to \eta' K_L$ (η_{cp}=+1)
Br=63.2+/- 3.3 x10^{-6}

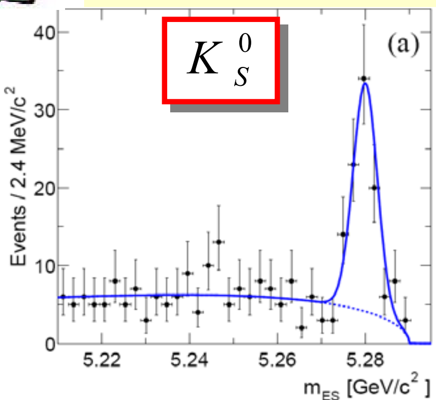
$B \to f^0 K_s$ (η_{cp}=+1) Br=1/2(5.5+/-1.0 x10^{-6})

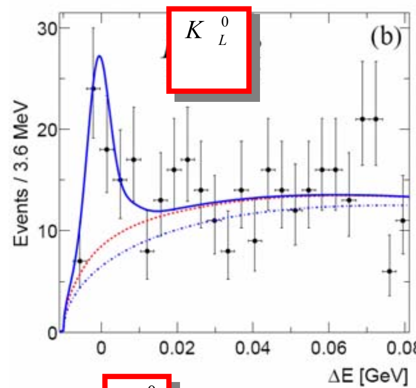
$b \to s d\bar{d}$:

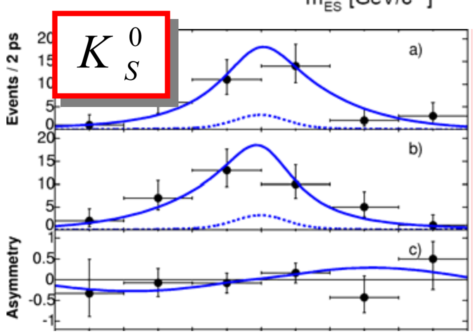
$B \to \pi^0 K_s$ (η_{cp}=-1) Br=1/2(11.5+/-1.0) x10^{-6}
$B \to \omega K_s$ (η_{cp}=-1) Br=1/2(4.7+/-0.6) x10^{-6}

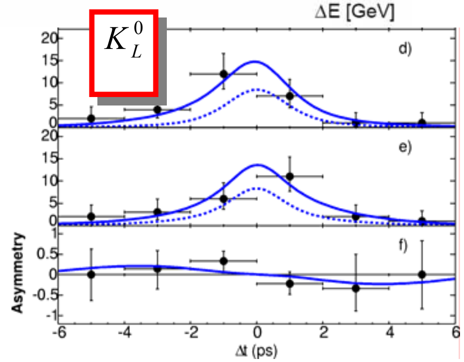
The Data: ϕK_s, $K^+K^-K_s$

232×10^6 $B\bar{B}$'s

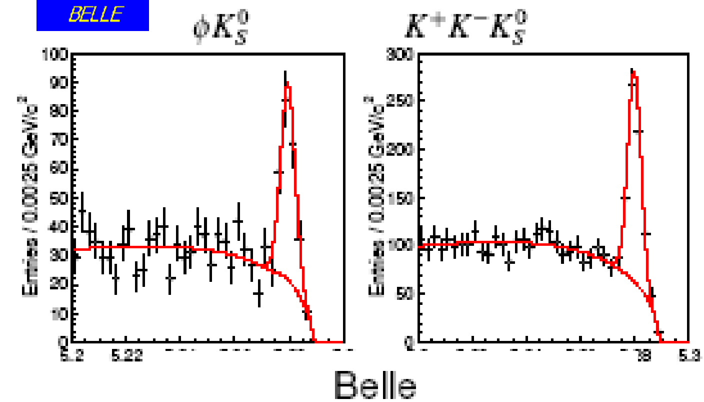


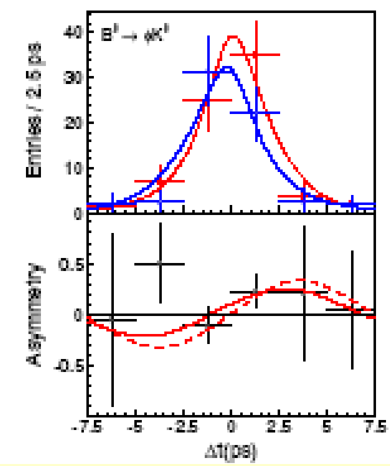






Belle ($386\times10^6 B\bar{B}$)





$$-\eta_{\chi\pi} S_{\phi K_s} = +0.50 \pm 0.25^{+0.07}_{-0.04}$$

$$C_{\phi K_s} = +0.00 \pm 0.23 \pm 0.05$$

$$-\eta_{\chi\pi} S_{K^+K^-K_s} = +0.55 \pm 0.22 \pm 0.04 \pm 0.11(cp)$$

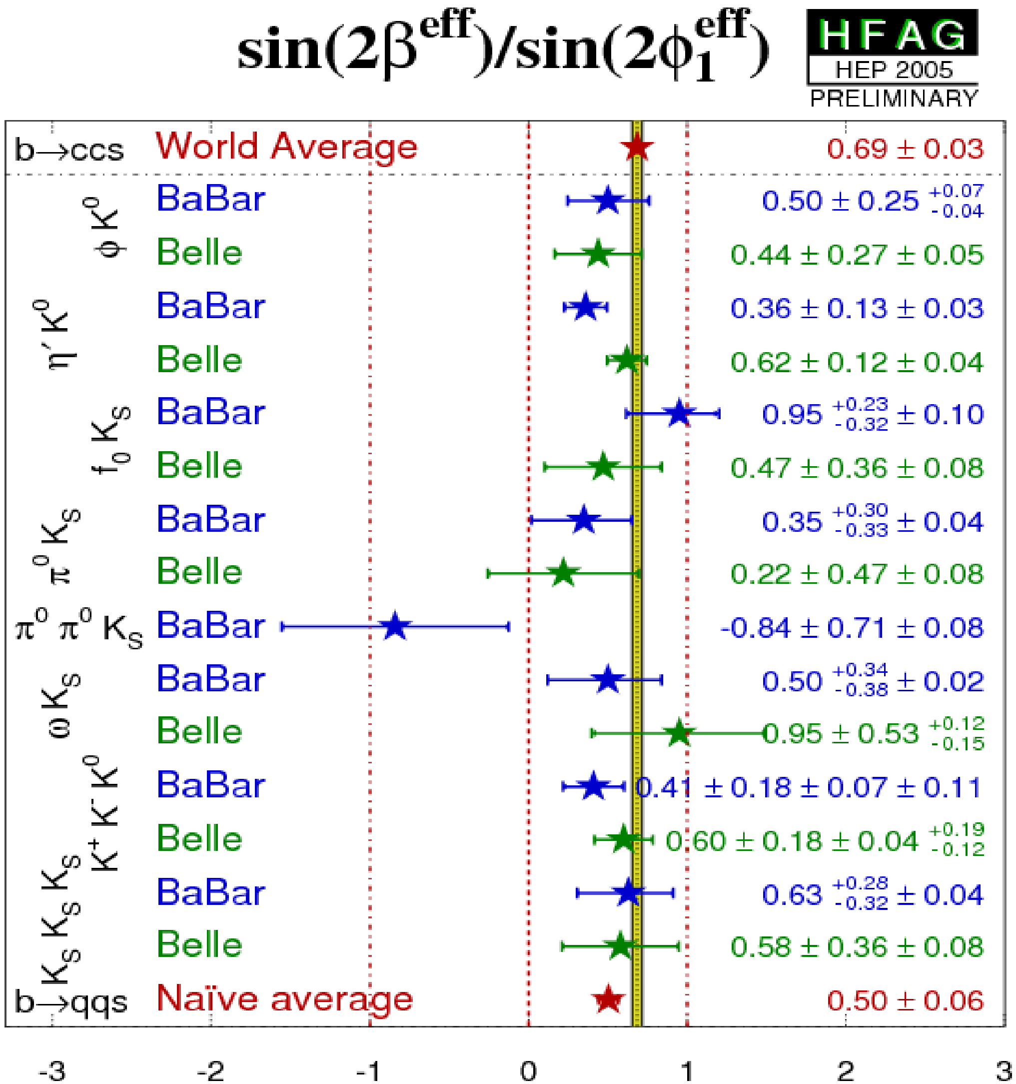
$$-\eta_{\chi\pi} S_{K_sK_sK_L} = +0.09 \pm 0.33 \pm^{0.13}_{0.14} \pm 0.10(cp)$$

$$-\eta_{\chi\pi} S_{\phi K_s} = +0.44 \pm 0.27 \pm 0.05$$

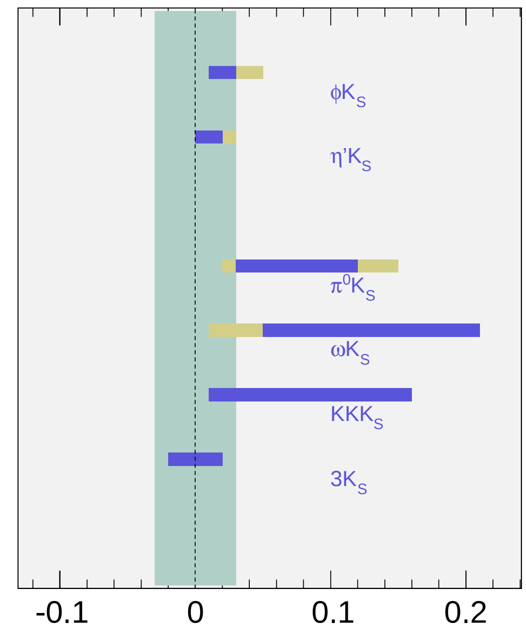
$$C_{\phi K_s} = +0.14 \pm 0.17 \pm 0.07$$

$$-\eta_{\chi\pi} S_{K^+K^-K_s} = +0.60 \pm 0.18 \pm 0.04 \pm^{0.19}_{0.12}(cp)$$

Similarly all other channels are also statistically limited-



QCD factorization calculation of ΔS



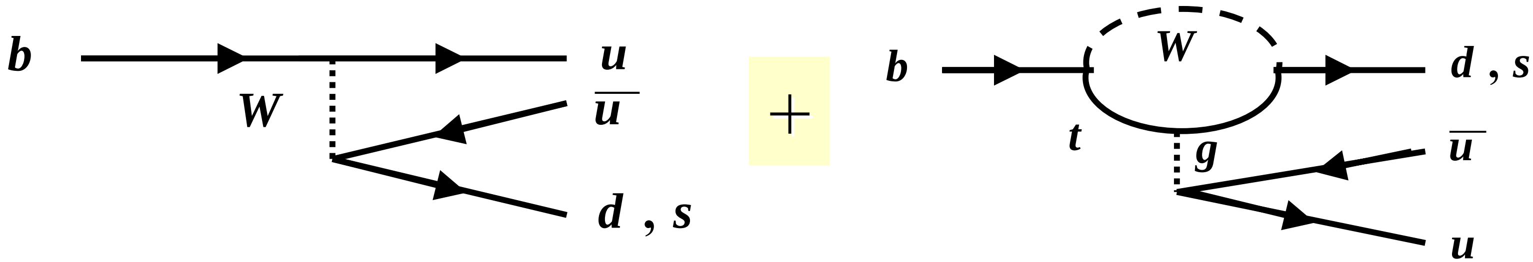
Simple average: $S_{penguins}$**=0.5 +/- 0.06 vs reference point: sin2β=0.69+/-0.03**

~ 2.5 σ deviation at this point.

- **Tests with Direct CP violations**

Direct CP violation results when several diagrams, with different cp conserving and cp breaking phases contributing to the same final state, interfere:

E.g. B→Kπ: B→Kπ: ($K^+ \pi^-$, $K^0 \pi^+$, $K^0 \pi^0$, ..)



$$A = -(|T|e^{i\gamma} + |P|e^{i\delta}) \qquad \overline{A} = -(|T|e^{-i\gamma} + |P|e^{i\delta})$$

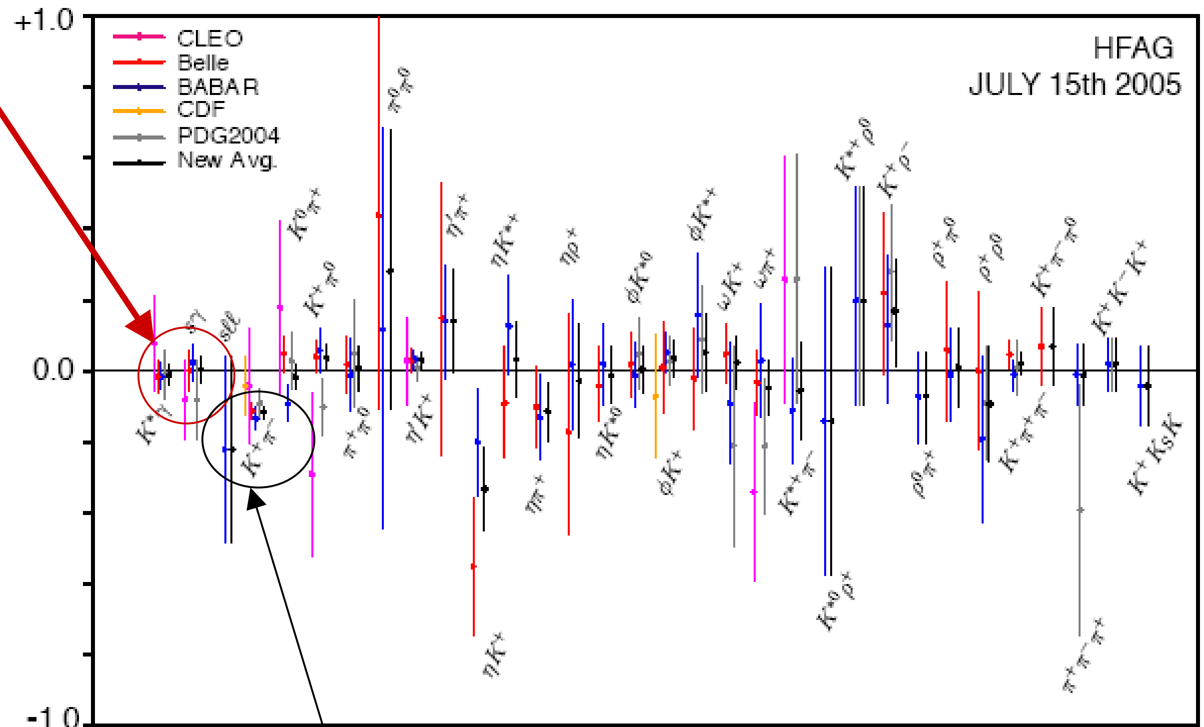
$$A_{cp} = \frac{\Gamma(\overline{B}\to\overline{f}) - \Gamma(B\to f)}{\Gamma(B\to f) + \Gamma(\overline{B}\to\overline{f})} = -2\left|\frac{P}{T}\right| \sin\delta \, \sin\gamma$$

A contributing diagram from "New Physics" can alter A_{cp} from the SM values. Need predictions of A_{cp} within SM- Again rely on QCDF or PQCD, or exploit symmetries (SU2, SU3 etc) to connect A_{cp} in different modes and derive sum rules- to be tested.

Within SM: Expect $A_{cp}(b \to s\gamma) \sim 0$

Mode	New Avg.
$K^*\gamma$	-0.010 ± 0.028
$s\gamma$	0.004 ± 0.036
$s\ell\ell$	-0.22 ± 0.26

CP Asymmetry in Charmless B Decays

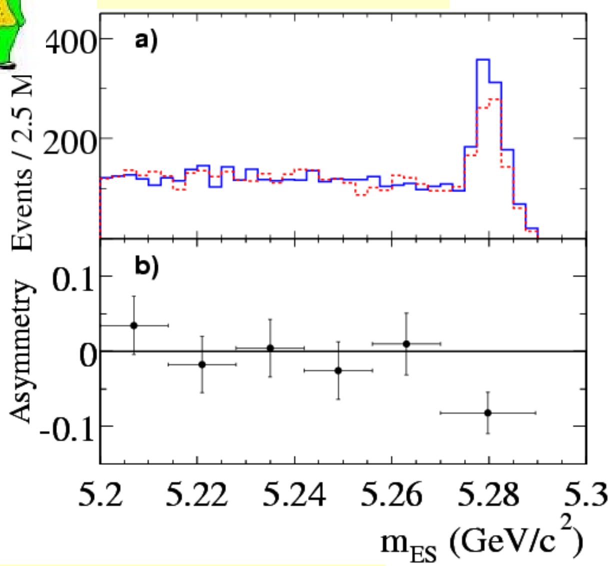


$A_{cp}(B^0 \to K^+\pi^-) = -0.115 +/- 0.018$

So far the only confirmed case for direct CP violation in B decays

Observation of direct CP violation in $B^0 \rightarrow K^+\pi^-$

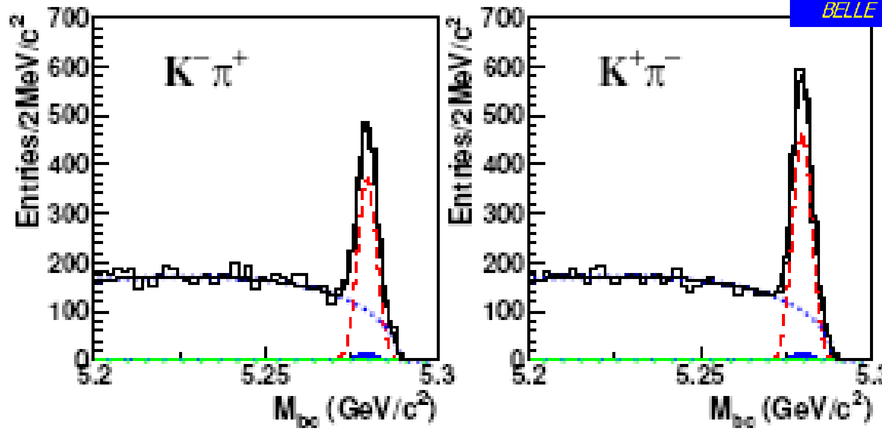
$232\times10^6\ B\bar{B}$'s



BaBar 2004

$$A_{CP} = -0.133 \pm 0.030 \pm 0.009$$

Belle ($386 \times 10^6 B\bar{B}$)



New Belle Result:
-0.113+/- 0.022+/- 0.008

HFAG Average -0.115+/- 0.018

➔superweak is really out; Strong phases are non-zero in these decays- one more challenge for QCD to explain quantitatively.

Within the SM, direct A_{cp}'s for all $B\to K\pi$ modes are related-

$A_{cp}(B^0 \to K^+\pi^-)$ = -0.115+/- 0.018

$A_{cp}(B^0 \to K^0\pi^0)$ = +0.02+/- 0.13

$A_{cp}(B^+ \to K^+\pi^0)$ = +0.04+/- 0.04

$A_{cp}(B^+ \to K^0\pi^+)$ = -0.02+/- 0.04

•Naive expectation: $A_{cp}(B^0 \to K^+\pi^-) \approx A_{cp}(B^+ \to K^+\pi^0)$

The test fails– New Physics or too naïve?

A more accurate sum rule relation derived based on SU(2) and SU(3) relations- (M. Gronau hep-ph/0508047)

$$A_{cp}(B^0 \to K^+\pi^-) + A_{cp}(B^+ \to K^0\pi^+) \approx A_{cp}(B^+ \to K^+\pi^0) + A_{cp}(B^0 \to K^0\pi^0)$$

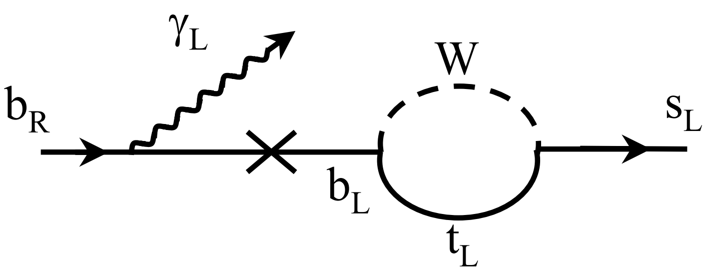
To satisfy this relation requires: (accounting for τ_{B0}, τ_{B+}, & br. differences)

$A^{expected}_{cp}(B^0 \to K^0\pi^0)$ = -0.17+/- 0.06 vs measured **$A_{cp}(B^0 \to K^0\pi^0)$ = +0.02+/- 0.13** .

(Needs more data)

- **Polarization effects- Revisit $b \to s\gamma$:**

EW: $b \to s\gamma$ & $b \to s l^+ l^-$



Measured rate consistent with SM:

$BF(b \to s\gamma)_{TH}$ = $3.57 \pm 0.30 \times 10^{-4}$ (SM NLO)

$BF(b \to s\gamma)_{EXP}$ = $3.54 \pm 0.30 \times 10^{-4}$ (HFAG)

(See Jeff Richman's talk this conf.)

But there is more info in this process:

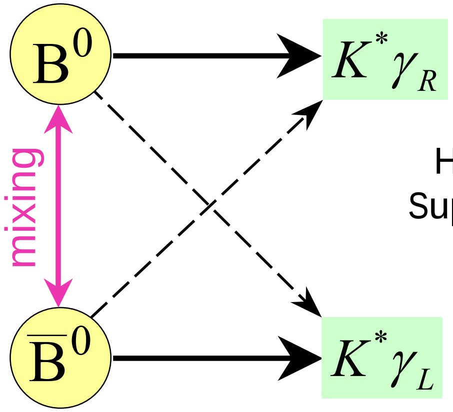
In the SM:

- **$b \to \gamma s_L$ (γ left-handed)**
- **Direct CP violation – nearly zero**

New physics contributions can result in mixed polarization for γ (& non-zero direct CPV)

Probing the γ–polarization via Time-dependent CP violation in b→sγ decays

(A. Atwood, M. Gronau & A. Soni (1997))



$$A_{cp}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{cp}\gamma) - \Gamma(B^0(t) \to f_{cp}\gamma)}{\Gamma(\bar{B}^0(t) \to f_{cp}\gamma) + \Gamma(B^0(t) \to f_{cp}\gamma)} = S_{fcp\gamma} \sin\Delta mt - C_{fcp\gamma} \cos\Delta mt$$

Helicity Flip
Suppressed by
~ m_s/m_b

$$S_{fcp\gamma} \propto \eta_{cp} \frac{A(\bar{B}^0 \to f_{cp}\gamma_R)}{A(\bar{B} \to f_{cp}\gamma_L)} \sin 2\beta$$

Within SM

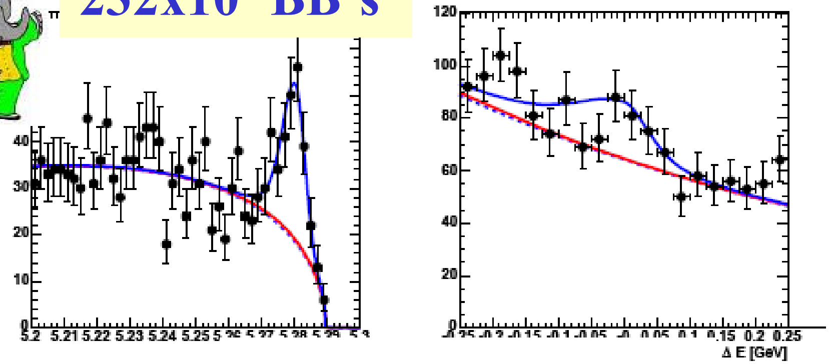
$$S_{fcp\gamma} = \frac{-2m_s}{m_b} \sin 2\beta \approx -0.035$$

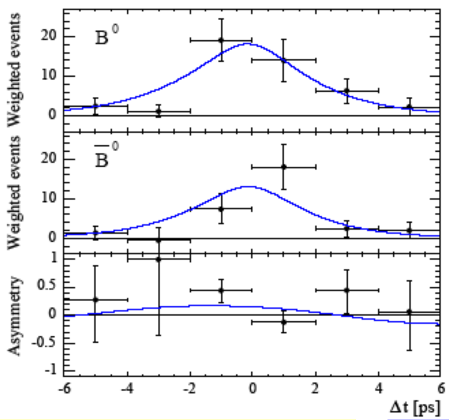
The value of $S_{K^*\gamma}$ as a NP observable depends on SM uncertainties - recent work based on QCDF/SCET, considering the impact of b→sγ(g) set **$S_{K^*\gamma}$**~ 0.1 **-** (*Grinstein, Grossman, Ligeti, Pirjol PRD 71, 011504(2005), Grinstein, Pirjol, hep-ph/0510104*)

TDCP analysis requires modes common to B0 and B0(bar): e.g.

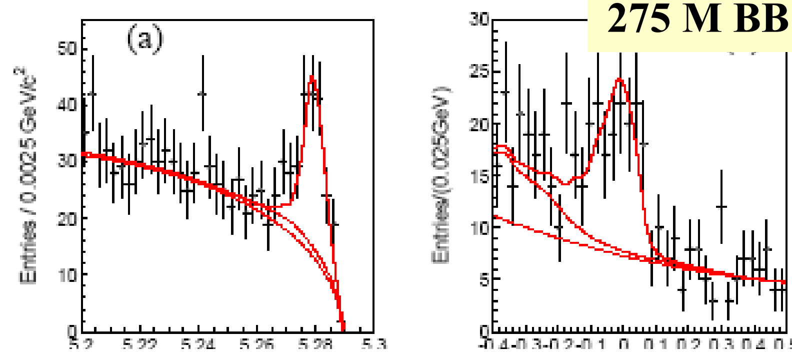
$B \to K^*(890)\gamma$ with $K^* \to K^0 \pi^0$, $K^0 \to K_s \to \pi^+\pi^-$ with $Br \sim 13.4\times10^{-6}$

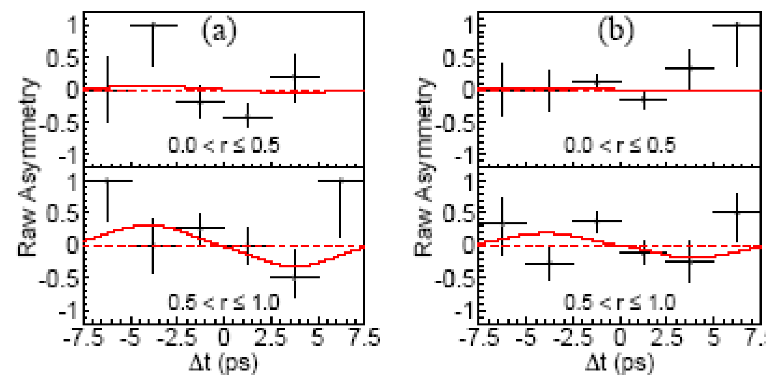
232×10^6 $B\bar{B}$'s





275 M BB's





$S_{K^*\gamma}$ **=-0.21 +/- 0.40 +/- 0.05**

$C_{K^*\gamma}$ **= -0.40 +/- 0.23 +/- 0.04**

$S_{K_s\pi^0\gamma}$ **=-0.21 +/- 0.40 +/- 0.05**

$C_{K\pi^0\gamma}$ **= -0.40 +/- 0.23 +/- 0.03**

HFAG Average:

$S_{K^*\gamma}$ **=-0.13 +/- 0.32**

$C_{K^*\gamma}$ **= -0.31 +/0.19**

$S_{K^*\gamma}$ **=0.01 +/- 0.51 +/- 0.11**

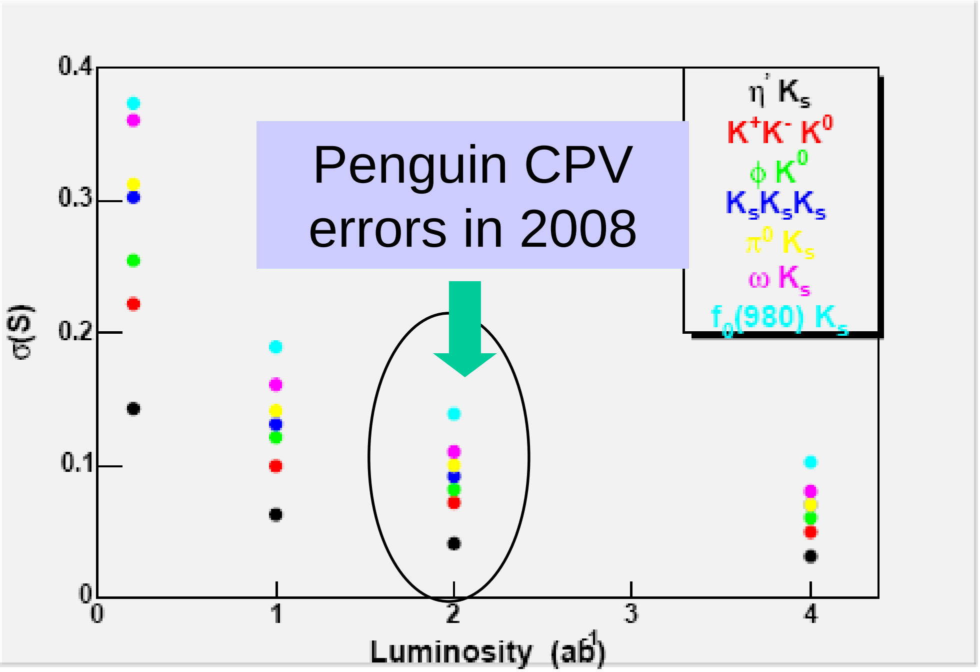
$C_{K^*\gamma}$ **= -0.11 +/- 0.33 +/- 0.09**

Needs much more data

SM: $S_{K^*\gamma} \sim 0.1$

Summary & Outlook

➢**BaBar & Belle are aiming for around 1 ab^{-1} of data each by 2008**



Uncertainties in most Direct CP asymmetries to follow sqrt(n) to ~1% level.

➢**Together with the CKM unitarity tests, this could soon either lead to signs of Physics beyond the SM In the flavor sector (a 2 to 3 σ deviation from the SM is present now) , and/or to a precisely constrained charged current sector of the Electroweak theory as a reference point for future searches for New Physics.**